DEPARTMENT OF ELECTRICAL ENGINEERING

A Report On

"Advanced Power Electronics For Solar PV Integration"

A training program organized under the NCPRE

National Centre for Photovoltaic Research and Education (NCPRE)

Department of Electrical Engineering IIT Bombay

17th to 19th July 2025

Submitted By :-

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Acknowledgment

We would like to express our heartfelt gratitude to **NCPRE** And **IIT Bombay** for providing us the opportunity to attend the 3-Day Training Program on “Advanced Power Electronics for Solar PV Integration”, conducted under the National Centre for Photovoltaic Research and Education (NCPRE).

We extend our sincere thanks to the Course Coordinators, **Prof. Shiladri Chakraborty** and **Prof. B. G. Fernandes**, for organizing this highly informative and enriching training program. We are also deeply grateful to the Course Instructors, **Prof. Sandeep Anand, Prof. Kishore Chatterjee,** and **Prof. Anil Kulkarni** for their valuable knowledge, insightful lectures, and practical demonstrations that enhanced our understanding of advanced power electronics and solar PV integration.

We would also like to acknowledge **Ms. Diksha Makwani,** Senior Executive Officer, NCPRE, Department of Electrical Engineering, IIT Bombay, for her continuous support, guidance, and smooth coordination during the entire course.

Finally, we express our gratitude to our college and **Dr. S. M. Shinde Sir** for giving us this opportunity, who contributed to making this training program a successful and memorable experience.

Contents :-

About the NCPRE and IIT Bombay

Indian Institute of Technology Bombay (IIT Bombay) Established in 1958, IIT Bombay is one of India's premier engineering institutions, renowned globally for excellence in education, research, and innovation. Located in Powai, Mumbai, it is recognized for its contributions to science, technology, and industrial development. The institute hosts world-class laboratories, advanced research centers, and has a strong network with industries and academia across the globe.

National Centre for Photovoltaic Research and Education (NCPRE)

The National Centre for Photovoltaic Research and Education (NCPRE) at IIT Bombay was established in 2010 with support from the Ministry of New and Renewable Energy (MNRE), Government of India. It aims to support India's ambitious 100 GW solar mission through cutting-edge research, technology development, and education.

NCPRE works across 8 departments, involving 39 faculty members and over 120 researchers, focusing on both basic and applied photovoltaic research. Key areas include:

Solar cell fabrication and characterization

Power electronics for PV systems

Energy storage and batteries

Module reliability and policy research

The centre also engages in industry collaboration, offers measurement and consultancy services, and runs short-term courses for students, faculty, and professionals to disseminate the latest developments in solar PV technology.

Leadership Team:

PIs: Prof. Baylon G. Fernandes,

Prof. Chetan Singh Solanki

Co-PIs: Prof. Sagar Mitra,

Prof. Anil Kottantharayil

Objective of Training Program :-

The primary objective of the 3-Day Training Program on "Advanced Power Electronics for Solar PV Integration" was to provide participants with an in-depth understanding of modern power electronic technologies essential for efficient and reliable solar photovoltaic (PV) integration into the grid.

As solar energy adoption accelerates, advanced power electronics are key to unlocking high-efficiency, reliable, and grid-compliant PV systems. This intensive three-day course offers a deep dive into modern inverter architectures and semiconductor technologies crucial for solar PV integration. Participants will learn about single-stage and multistage inverter topologies, modulation schemes, wide bandgap devices (SiC/GaN), energy buffering techniques, and advanced control strategies for gridtied systems. The course features a rich blend of lectures and hands-on sessions—including LTSpice simulations, real-time hardware demos, and DSP based inverter control—designed to bridge theory with practical application. Ideal for graduate students, R&D engineers, and professionals in the renewable energy sector, this program will equip attendees with the technical know-how and practical skills to design and analyze next-generation PV power conversion systems.

This program was designed to:

1. Enhance Technical Knowledge

- ✓ Provide a comprehensive review of PV power electronic systems and advanced inverter topologies, including single-stage, multi-stage, isolated, and non-isolated architectures.
- ✓ Introduce wide band gap semiconductor devices (SiC/GaN) and their applications in high-efficiency inverter systems.

2. Develop Practical Skills

- ✓ Offer hands-on experience through LT Spice simulations, real-time hardware demonstrations, and DSP-based inverter control to bridge the gap between theory and practical applications.
- ✓ Train participants in gate-driver design, advanced magnetics, and energy buffering techniques for next-generation power conversion systems.

3. Build Competence for Grid Integration

- ✓ Familiarize participants with advanced control strategies for grid-tied PV inverters and explore emerging trends in grid integration and future PV technologies.

4. Promote Research and Innovation

- ✓ Equip graduate students, R&D engineers, and renewable energy professionals with the skills and insights necessary for designing, analyzing, and innovating in solar PV power electronics systems.

By the end of the course, participants gained a solid foundation in both theoretical concepts and practical implementations, enabling them to contribute effectively to the advancement of solar PV power conversion technologies.

1. Group Photograph captured on first day session

Day Wise Schedule and Activities :-

Day 1 (Thursday)			
Time	**Session**	**Location**	**Instructors**
9:00 AM - 9:30 AM	Registration Introduction and welcome to participants Overview of NCPRE	GG301	Prof. Harish K. Pillai Prof. Baylon G. Fernandes Prof. Shiladri Chakraborty
9:30 AM - 10:45 AM	Lecture 1: Review of PV power electronic systems	GG301	Prof. Kishore Chatterjee
Tea/Coffee Break			
11:15 AM - 12:30 PM	Lecture 2: Advanced inverter circuits: non-isolated	GG301	Prof. Baylon G. Fernandes
1:00 PM - 2:00 PM	Lunch - Padmavihar Guest House Dining Hall		
2:30 PM - 3:45 PM	Lecture 3: Advanced power semiconductor (WBG) devices & applications ckts.	Collaborative Classroom (4th floor, GG)	Prof. Sandeep Anand
Tea/Coffee Break			
4:15 PM - 5:30 PM	Hands-on demo session 1: LTSpice	Collaborative Classroom (4th floor, GG)	Prof. Shiladri Chakraborty & TAs
5:30 - 6:30 PM	Lab visits (optional)		

Day 2 (Friday)			
Time	**Session**	**Location**	**Instructors**
9:30 AM–10:45 AM	Lecture 5: Advanced inverter circuits: isolated 1	GG 301	Prof. Shiladri Chakraborty
Tea/Coffee Break			
11:15 AM - 12:30 PM	Lecture 6: Gate-driver design for WBG devices	GG 301	Prof. Sandeep Anand
1:00 PM - 2:00 PM	Lunch - Padmavihar Guest House Dining Hall		
2:30 PM–3:45 PM	Lecture 7: Advanced inverter circuits: isolated 2	GG 301	Prof. Shiladri Chakraborty
Tea/Coffee Break			
4:15 PM - 5:30 PM	Lecture 8: Grid integration (AMK)	GG 301	Prof. Anil Kulkarni
5:30 PM - 6:30 PM	Lab visits (optional)		

Day 3 (Saturday)			
Time	**Session**	**Location**	**Instructors**
9:30 AM–10:45 AM	Lecture 9: Advanced inverter circuits: single-phase energy buffering	GG 301	Prof. Baylon G. Fernandes
Tea/Coffee Break			
11:15 AM - 12:30 PM	Hands-on demo session 2: TI DSP, WBG DPT	GG001, GG002, Machines lab	TAs
1:00 PM - 2:00 PM	Lunch - Padmavihar Guest House Dining Hall		
2:15 PM - 3:30 PM	Hands-on demo session 3: TI DSP, WBG DPT	GG001, GG002, Machines lab	TAs
Tea/Coffee Break			
3:45 PM - 5:00 PM	Lecture 10: Advanced high-frequency magnetics for power electronics	GG 301	Prof. Shiladri Chakraborty
5:15 PM - 5:45 PM	Concluding session	GG 301	

Day 1 Sessions :-

Lecture 1: Review of PV Power Electronic Systems

Instructor: **Prof. Kishore Chatterjee**, IIT Bombay

The first lecture of the training program provided a comprehensive review of photovoltaic (PV) power electronic systems, focusing on the behavior of PV arrays, the need for maximum power extraction, and the role of power electronic converters in modern solar PV integration.

1. **Introduction to Solar PV in India**
   - The session began with an overview of the National Solar Mission (2008) , which set a target of generating 100 GW (100,000 MW) of solar power by 2022.
   - Emphasis was laid on both large-scale grid-connected PV plants and decentralized rural deployments.
   - Solar PV was highlighted as an abundant, clean, and low-maintenance energy source, though it faces challenges such as low energy density, scalability issues, and the requirement of energy storage for consistent supply.

2. **PV Array Characteristics**
   - The lecture explained the current-voltage (I-V) and power-voltage (P-V) characteristics of solar arrays, showing how load resistance, solar irradiance, and temperature affect the output power.
   - The concept of matching load to the PV array to achieve maximum power output was introduced, emphasizing the need to operate at the Maximum Power Point (MPP) for efficient energy extraction.

3. **Maximum Power Point Tracking (MPPT)**
   - To ensure maximum energy harvesting from a PV system, MPPT techniques were discussed in detail.
   - Prof. Chatterjee explained how the P-V curve shifts with irradiance and temperature changes and why tracking the MPP is crucial. Common MPPT methods presented included: Incremental Conductance. Using the slope of the I-V curve to detect the exact MPP.

4. **Power Electronic Converters for PV Systems**
   - The role of DC-DC converters and DC-AC inverters in PV systems was discussed extensively.
   - Boost Converters were presented as an example of how to interface a PV array to a DC load while maintaining MPP operation.
   - For AC loads, inverters are essential. Both Square Wave and Sinusoidal Pulse Width Modulation (SPWM) inverters were explained, including their operation principles, harmonic spectra, and output characteristics.

5. **Grid-Connected PV Systems**
   - The lecture covered the basics of grid-tied solar PV systems, including single-stage and two-stage inverter configurations.
   - Key elements of grid connection such as Phase Locked Loop (PLL) for synchronization, harmonic control, and reactive power support were explained.
   - The types of grid-connected inverters Central, String, Multi-string, and Micro-inverters were also introduced.

6. **Islanding and Grid Safety**
   - A critical part of grid integration is islanding detection, which ensures that PV inverters disconnect safely when the grid fails, preventing backfeeding.
   - Both active and passive islanding detection methodswere discussed, including communication-based techniques and switched capacitor methods.

At the end of the session, Prof. Kishore Chatterjee concluded the lecture by summarizing the key concepts and addressed participants' questions and doubts, making the session highly interactive and insightful

1.1 Lecture on Review of PV Power Electronic Systems

1.2 Lecture on Review of PV Power Electronic Systems

1.3 At the end of lecture Question and answer session

Lecture 2: Advanced Inverter Circuit Non- Isolated

Instructor: **Prof. B.G. Fernandes**, IIT Bombay

This lecture focused on non-isolated inverter architectures for grid-connected solar PV systems, with an emphasis on transformerless designs to improve efficiency and reduce size and weight.

1. Grid-Connected Inverter Fundamentals

- Prof. Fernandes explained that grid-connected PV inverters convert DC output from solar panels into AC to be supplied directly to the grid, typically without battery storage.
- The power flow to the grid is determined by the phase angle between the inverter and the grid voltage, and controlling this phase allows precise regulation of the power injected.

2. Pulse-Width Modulation (PWM) Techniques

- The lecture introduced the two primary modulation methods for transformerless inverters:
- Bipolar SPWM (Sinusoidal Pulse Width Modulation): Produces lower harmonic distortion in voltage but results in higher current ripple and slightly lower efficiency.
- Unipolar SPWM: Uses out-of-phase control signals, resulting in lower current ripple, better efficiency, and easier harmonic filtering, making it more suitable for transformerless PV systems.

3. Transformerless Inverters

- Transformerless inverters eliminate low-frequency (LF) or high-frequency (HF) isolation transformers, making them compact, light, and more efficient.
- The major challenge is earth leakage current, caused by the parasitic capacitance between PV panel terminals and the grounded frame, which is excited by high-frequency switching.

4. Leakage Current Mitigation

- Coupled inductors and common-mode voltage (vCM) control are used to suppress leakage currents.

- Advanced topologies such as Neutral Point Clamped (NPC), H5, HERIC, and OH5 were discussed in detail.
- NPC and H5 topologies maintain a constant common-mode voltage, minimizing high-frequency leakage currents and improving electromagnetic compatibility (EMI).

5. Advantages and Limitations

- Advantages: High efficiency (up to 98%), lower weight and cost, and suitability for large-scale PV deployment.
- Limitations: Sensitive to switching patterns, requires careful leakage current management, and may need advanced filtering techniques to meet safety standards.

At the end of the lecture, Prof. Fernandes summarized the practical trade-offs in transformerless inverter designs and conducted a question-and-answer session to clarify participants' doubts.

1.4 Prof. B.G. Fernandes Delivering lecture

1.5 Interactive discussion between participants and speaker during session

1.6 Participants attending the session for prof. B. G. Fernandes

Lecture 3: Advanced Power Semiconductor Wide Bandgap (WBG) Devices and Applications

Instructor: **Prof. Sandeep Anand,** IIT Bombay

This lecture introduced Wide Bandgap (WBG) semiconductor devices and their applications in solar PV inverters and high-efficiency power conversion systems. The session emphasized how WBG technologies, particularly Silicon Carbide (SiC) and Gallium Nitride (GaN), are enabling the next generation of compact, efficient, and reliable** PV systems.

1. Introduction to Wide Bandgap Devices

- SiC MOSFETs and GaN HEMTs exhibit higher breakdown electric fields, faster switching speeds, and lower switching/conduction losses than traditional silicon devices.
- SiC is well-suited for high-voltage, high-power applications such as medium-voltage PV inverters and EV fast chargers, whereas GaN is commonly used in low-voltage and high-frequency converters.

2. Benefits and Applications

- Medium-voltage PV inverters can now operate at 1.5 kV to 3.3 kV, reducing the need for bulky low-frequency transformers and decreasing system losses.
- WBG devices help design compact, lightweight, and highly efficient solar inverters, battery converters, and EV fast chargers.
- Utility-scale solar plants increasingly rely on SiC-based central inverters to achieve higher efficiency and reliability.

3. Device Characteristics

- Prof. Anand explained the differences between MOSFETs and IGBTs and how WBG devices overcome the limitations of silicon by providing:
  Lower ON-resistance and faster switching
  Higher power density and better thermal performance
  Reduced losses and cooling requirements

Practical Design Considerations

- While WBG devices provide clear efficiency advantages, they also introduce design challenges like:

- High dv/dt and di/dt effects causing EMI and stress on insulation.
- Increased sensitivity to layout parasitics and loop inductance.
- Industry trends and examples, such as SiC-based 1.5 kV PV inverters in Germany and China, were shared to illustrate current global adoption.

At the end of the session, Prof. Anand concluded by highlighting that WBG devices are a cornerstone for next-generation PV and EV systems, and he addressed participants' queries regarding their practical applications.

1.7 Session on Advanced Power Semiconductor Wide Bandgap (WBG) Devices and Applications

1.8 Prof. Sandeep Anand delivering lecture

Hands-on Demo Session 1: LTSpice Simulation for Power Electronics

Conducted by Prof. Shiladri Chakraborty

A practical hands-on demonstration session was conducted to familiarize participants with LTSpice, a widely used circuit simulation software, specifically for power electronic applications.

Objective of the Session: The main aim of the session was to enable participants to:

- Understand the simulation environment of LTspice.
- Learn how to model basic power converter circuits, particularly DC-DC and inverter circuits relevant to PV systems.
- Analyze circuit behavior, waveforms, and switching characteristics through simulation.

Key Activities and Learnings :

- Participants were guided through the LTSpice interface, including component selection, schematic creation, parameter editing, and waveform viewing.
- A basic Boost Converter circuit was designed and simulated, showing the effects of component values on output voltage and switching behavior.
- Emphasis was placed on time-domain simulation, transient response analysis, and observing inductor current and switch voltage waveforms.
- Techniques for using voltage and current probes, setting initial conditions, and exporting waveforms were demonstrated.
- Prof. Chakraborty explained how simulation helps in pre-verifying converter designs before hardware implementation, thereby reducing trial-and-error in lab setups.

Outcome of the Session:

- By the end of the session, participants were able to:
- Develop and simulate simple power electronic circuits using LTSpice.
- Interpret simulation waveforms and relate them to real converter operation.

- Appreciate the importance of simulation tools in the design and analysis of PV-integrated power electronics systems.

The session was interactive and hands-on, allowing each participant to run their own simulations and clarify doubts directly with Prof. Chakraborty, making it a valuable foundation for the lab sessions to follow in the coming days.

1.9 Hands on Demo session by participants

1.10 Hands on Demo session by participants

Day 2 Sessions :-

Lecture 5: Advanced inverter circuit Isolated – 1

Instructor: **Prof. Shiladri Chakraborty**, IIT Bombay

Topic: Isolated DC-DC Converters
This lecture introduced the concept, importance, and various topologies of isolated DC-DC converters, focusing on their application in solar PV power electronics systems.

1. Why Use Isolated Converters in PV Systems?

- Offers high-frequency galvanic isolation, reducing ground leakage currents compared to transformerless inverters.
- Enables voltage step-up/down efficiently, especially in low-voltage DC to high-voltage AC applications.
- Supports compact design and better volt-amp utilization.
- Allows soft-switching, reducing switching losses.

2. Converter Topologies Covered:

Phase-Shifted Full-Bridge (PSFB):

- A resonant-transition converter, widely used in medium to high-power applications.
- Functions as an isolated buck converter with near-50% duty and phase shift between switches.
- Multiple configurations: unidirectional/bidirectional, voltage-fed/current-fed.
- **Challenge:** Voltage ringing due to transformer leakage inductance.
- **Solutions:** Clamping diodes, active snubber circuits, and flyback-based techniques.

Load-Resonant Converters:

- Series, Parallel, and LLC tanks discussed.
- LLC is the most commonly used due to its good part-load efficiency, short-circuit protection,
- and soft-switching (ZVS/ZCS) capability.
- Emphasis was laid on gain curves, operating points (above, below, and at resonance), and
- hardware-dependent performance.

Lecture 6: Gate Driver Design for Wide Bandgap (WBG) Devices

Instructor: **Prof. Sandeep Anand,** Department of Electrical Engineering, IIT Bombay

This lecture focused on the gate driver design requirements and challenges for SiC and GaN devices in solar PV inverters and high-frequency power converters.

1. Importance of Gate Driver Design

- WBG devices operate at high switching speeds, which enable high efficiency and compact design but also introduce gate control complexities.
- Proper gate driver design is critical for reliability, safety, and maximizing performance.

2. Key Challenges in WBG Gate Driving

- High dv/dt and di/dt Effects: Can cause Miller turn-on, cross-talk, and parasitic oscillations in half-bridge circuits.
- Lead to voltage overshoot and increased switching losses.
- Common-Mode Currents: Flow through isolation capacitances and may lead to false triggering or EMI issues.
- Gate Oxide Reliability: High dv/dt can accelerate oxide degradation in SiC MOSFETs.

3. Solutions and Best Practices

- Layout Optimization: Minimize parasitic inductances using short and symmetrical PCB traces.
- Kelvin Source Connection: Reduces the impact of common source inductance for accurate gate control.
- Gate Loop Protection Techniques: Use of negative gate bias, Miller clamps, and ferrite beads to suppress false triggering and ringing.
- Active Gate Driving (AGD): Dynamically controls switching speeds to limit dv/dt and improve reliability.

4. Reliability and Lifetime Enhancement

- Discussed active thermal control and online health monitoring techniques for SiC-based inverters.
- Proper gate driver design can extend device lifetime by 25–40% by reducing thermal stress and switching-related degradation.

At the conclusion of the session, Prof. Anand demonstrated practical gate driver strategies and answered participants' questions about EMI suppression, layout design, and gate biasing for high-speed WBG devices

2.1 Prof. Sandeep Anand

Lecture 7: Advanced Inverter Circuits – Isolated Part 2

Instructor: **Prof. Shiladri Chakraborty**, IIT Bombay

Topic: Dual Active Bridge (DAB) Converters
This lecture delved into active-bridge converter architectures, with a focus on the Dual Active Bridge (DAB), a widely used topology in PV and battery-based power systems.

1. DAB Converter Overview:

- A type of isolated DC-DC converter where both input and output sides have full-bridge structures.
- Enables bidirectional power flow, making it ideal for PV-storage and microgrid applications.

2. Operating Principle & Waveforms:

- DAB uses a high-frequency transformer and phase-shift modulation between the primary and secondary bridges.
- Power transfer is controlled by the phase difference (Dϕ) between the two bridges.
- Allows soft-switching (ZVS) in appropriate operating zones, minimizing switching losses.

3. Design Considerations:

Calculated average input power and RMS current, revealing trade-offs between ZVS operation and current stress.
Inductor sizing (L) is critical:

- Affects minimum/maximum power transfer capabilities.
- Impacts current ripple and switching conditions.

4. Advanced Modulation Techniques:

Explored to overcome limitations of basic phase-shift control when input-output voltage ratio deviates from transformer turns ratio.
Introduced:

- Single Phase Shift (SPS)
- Dual Phase Shift (DPS)
- Triple Phase Shift (TPS)

Each offers better performance in terms of ZVS range, RMS current reduction, and efficiency optimization.
A case study highlighted how TPS significantly improved converter efficiency under wide voltage ranges.

These lectures together emphasized the critical role of isolation, soft-switching, and control strategies in designing efficient PV power conversion systems

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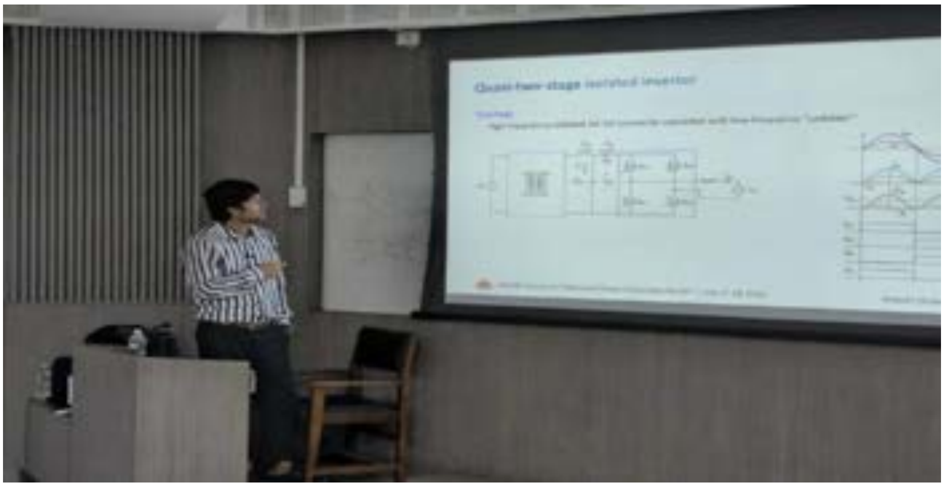


2.2 *Prof. Shiladri Chakraborty elaborating on DAB converter operations during Lecture 7*

2.3 *Participants noting down key concepts during an in-depth lecture session*

Lecture 8: Grid Integration of Solar PV System

Instructor: **Prof. Anil M. Kulkarni,** IIT Bombay

This lecture addressed the challenges, control strategies, and dynamic behavior of PV inverters in grid-connected applications, focusing on the differences between inverter-based resources (IBRs) and traditional synchronous generators.

1. Challenges of PV Grid Integration

- Generation Variability and Predictability: Solar output fluctuates with irradiance and weather conditions, impacting grid stability.
- Voltage Regulation and Reactive Power Support: Grid-connected PV inverters must provide voltage support and reactive power control.
- Disturbance Ride-Through: Inverters should stay connected during grid disturbances and avoid unnecessary tripping.
- Protection and Islanding: IBRs require advanced protection strategies and islanding detection mechanisms in distribution systems.

2. Inverter-Based Resource Behavior

- Grid-Following (GFL) Inverters: Depend on a PLL (Phase-Locked Loop) to synchronize with the grid, mainly injecting active and reactive power as per set points.
- Grid-Forming (GFM) Inverters: Can establish voltage and frequency autonomously and support black-start capabilities.
- GFM operation is crucial in weak grids, microgrids, and scenarios with high renewable penetration.

3. Dynamic Performance and Control

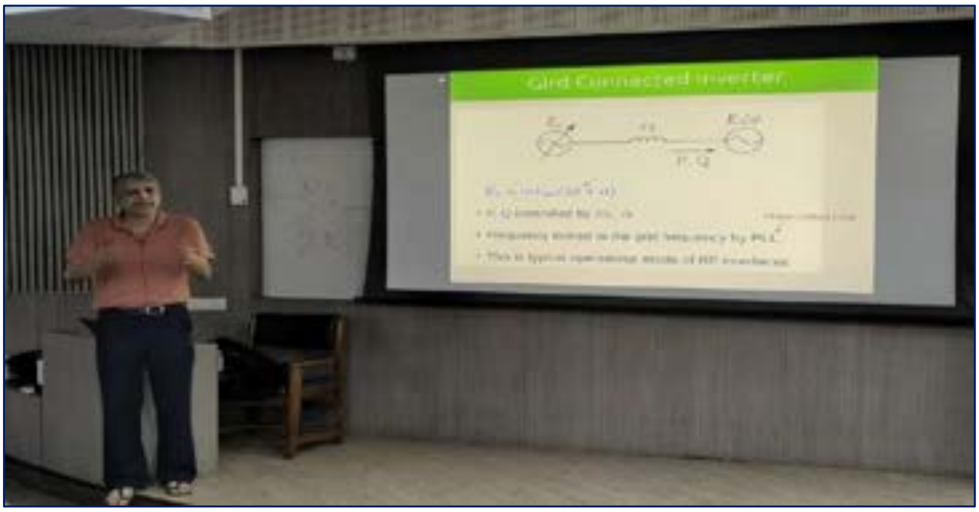
- Prof. Kulkarni explained the power-frequency droop concept, transient stability requirements, and current-limiting strategies during faults.
- Simulation tools such as Load Flow, RMS, and EMT models are used to study voltage stability, electromechanical dynamics, and fast transients

➢ He also discussed standards and compliance for inverter-based resources in Indian and international grids.

4. Practical Insights

➢ High renewable penetration requires careful transmission planning, advanced control strategies, and grid code adherence.
➢ Grid-forming inverters and hybrid control methods are essential for the future of stable PV integration.

Prof. Kulkarni concluded with real-world examples of grid interactions, shared simulation and measurement techniques, and addressed participants’ questions and doubts.



2.4 Prof. Anil Kulkarni delivering lecture

Day 3 Session :-

Lecture 9: Advanced Inverter Circuits – Single-Phase Energy Buffering

Instructor: **Prof. B.G. Fernandes**

This lecture covered inverter architectures tailored for single-phase PV systems, emphasizing the need for intermediate energy buffering to handle instantaneous power fluctuations between PV generation and grid delivery.

Key Concepts:

- In single-phase systems, the AC grid demands sinusoidal power, whereas the PV system provides constant DC. This mismatch creates a double-frequency ripple (2ω).
- To ensure stable operation and power quality, energy must be temporarily buffered using capacitors or inductors.

Buffering Techniques and Topologies:

- Presented circuit-level solutions integrating DC-DC converters with full-bridge inverters, enabling buffering.
- Introduced buffer capacitor voltage control techniques, such as:
- Voltage scaling approach
- Average power balancing
- Illustrated control methods to maintain constant input current and sinusoidal output current, ensuring unity power factor (UPF).

Performance & Efficiency:

- Emphasized maintaining low THD (Total Harmonic Distortion) and optimizing buffer size.
- Efficiency trade-offs and control complexity were discussed for both centralized and distributed buffering systems.

3.1 Prof. B.G. Fernandes explaining topologies during Lecture

3.2 Prof. B.G. Fernandes explaining topologies during Lecture

Lecture 10: Magnetics for Power Electronics

Instructor: **Prof. Shiladri Chakraborty**

This lecture emphasized the crucial role of magnetics in high-frequency power converters and detailed loss mechanisms, material choices, and design strategies for improving converter performance.

Importance of Magnetics:

- Magnetic components often dominate converter volume (\~80%) and losses (\~50%).
- Applications include transformers, inductors, and coupled devices in power supplies and inverters.

Loss Mechanisms:

- Core Losses: Due to hysteresis and eddy currents, affected by frequency and core material.
- Copper Losses: Skin effect and proximity effect dominate at higher switching frequencies.
- Illustrated examples of how winding geometry, frequency, and current distribution impact losses.

Design Considerations:

- Use of Litz wire, planar transformers, and interleaved windings to reduce AC resistance.
- Compared various core materials (Ferrites, Nanocrystalline, Powdered Iron) and their properties.
- Presented transformer models, including leakage inductance and capacitance impact on circuit behavior.

Practical Implications:

- Shared insights on size-to-efficiency tradeoffs, thermal management, and integration with PCB layout.
- Discussed emerging trends like 3D magnetic integration and hybrid magnetic structures.

3.3 Prof. Prof. Shiladri explaining terms during Lecture

3.4 Prof. Prof. Shiladri explaining terms during Lecture

Hands-on Demo Sessions 2 & 3: Double Pulse Testing (DPT), WBG, DSP

Conducted by: Prof. Shiladri Chakraborty and Team

At the conclusion of Day 3
, participants engaged in two highly interactive hands-on demonstration sessions designed to bridge the gap between theoretical concepts and practical system behavior in advanced power electronics.

1. DSP-Based Inverter Control (Texas Instruments Platform)

- Demonstrated the use of Digital Signal Processors (DSPs) for real-time control of grid-tied inverters
- Introduced the Texas Instruments DSP board setup, interfaced with gate drivers and inverter power stages.

Participants observed:

- PWM signal generation
- Sine wave tracking
- Grid synchronization using PLL
- Real-time response to load and voltage changes
- Discussed how closed-loop control is implemented in hardware using control algorithms (like PI and PR controllers).

Outcome:

- Participants understood how DSPs serve as the brain of modern inverters, providing precision control in solar PV applications.

2. Wide Bandgap (WBG) Gate Driver Demonstration

- Hands-on exploration of SiC and GaN switch gate driving, focusing on high-speed switching and protection features.
- Comparison between conventional silicon MOSFETs and WBG devices in terms of:
  - Switching loss
  - Gate charge
  - Driver requirements (isolation, dv/dt immunity)

Emphasized the need for:

- Fast rise/fall times
- Low parasitic inductance
- Negative gate voltage turn-off for SiC devices

Outcome:

Participants gained clarity on why WBG devices require specialized gate drivers, and how these impact efficiency and thermal design in inverters.

3. Double Pulse Testing (DPT) Fundamentals

Conducted a real-time Double Pulse Test (DPT) on a half-bridge circuit to measure switching characteristics.

Observed critical parameters:

- Turn-on and turn-off losses
- Voltage overshoot
- Current rise/fall times
- dv/dt and di/dt waveforms
-

Highlighted the effect of:

PCB layout
Stray inductance
Snubber and clamping techniques
Explained the importance of DPT in validating WBG devices under hard-switching conditions.

Outcome:

Participants learned how DPT is used to characterize and validate high-speed switches, a key step in converter design and safety assurance.

3.5 Group actively participating in circuit simulation during the hands-on workshop

3.6 Advanced inverter hardware prototype displayed during lab session

3.7 Exploring practical inverter configurations during lab demonstrations

Lab Visits

Day 1 :

1. C1973 EV Powertrain Lab

The first lab visit was to the Electric Vehicle (EV) Powertrain Lab, which focuses on the design, control, and testing of electric mobility systems.

Key Highlights:

- ✓ Demonstration of EV drive system components, including inverters, motors, battery management systems (BMS), and controllers.
- ✓ Participants observed the integration of power electronic converters with traction motors.
- ✓ Real-time testing of torque control, motor efficiency, and drive cycle simulations.
- ✓ Insightful discussion on vehicle-level optimization and energy regeneration in braking.

Learning Outcome:

Participants gained an understanding of how power electronics are central to modern EV systems, from motor control to battery integration.

3.1 Participants during the lab visit at the C1973 EV Power Train Lab

2. Medium Voltage Power Electronics Laboratory (MVPEL)

The second visit was to the MVPEL, which specializes in high-voltage converter systems, particularly relevant for utility-scale renewable energy integration.

Key Highlights:

- ✓ Exposure to medium voltage (3.3 kV+) converter prototypes, used in solar farms and microgrids.
- ✓ Demonstration of gate driver protection mechanisms, current/voltage sensing, and cooling systems.
- ✓ Safety protocols in high-voltage test environments were explained in detail.
- ✓ Participants observed setups used for hardware-in-loop (HIL) and EMT simulations.

Learning Outcome:

Attendees understood the design, challenges, and safety considerations in operating high-voltage inverters used for grid-connected solar PV systems.

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3.2 Structure of MVPEL

3. Solar Simulator and Characterization Lab

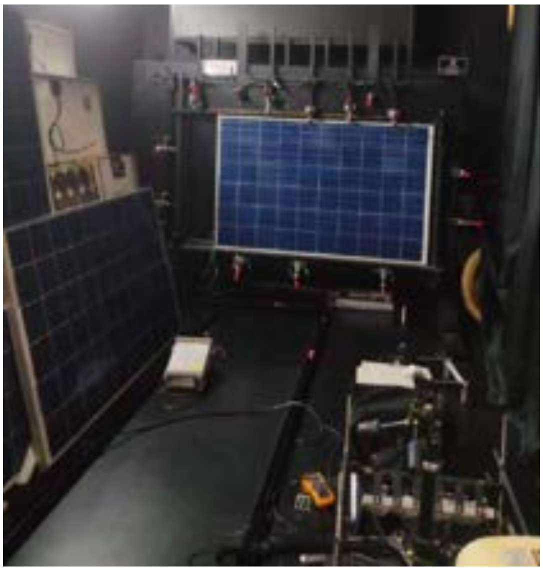
The final visit of Day 1 was to the Solar Simulator Lab, a core facility for testing and characterizing solar photovoltaic modules.

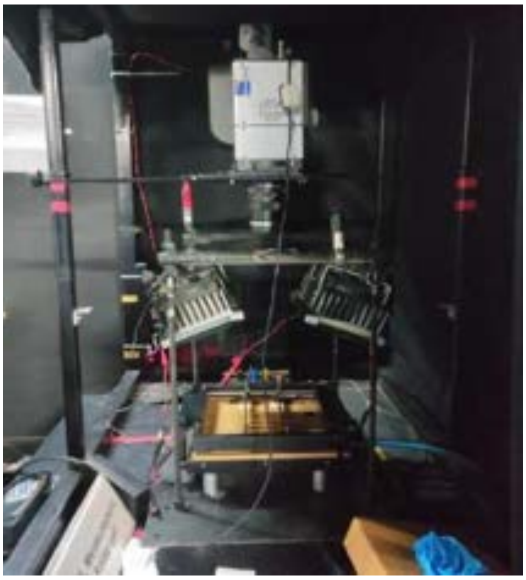
Key Highlights:

- ✓ Introduction to solar simulators that replicate standard sunlight conditions (AM 1.5 spectrum).
- ✓ Demonstration of I-V and P-V curve tracing, used to evaluate PV module performance.
- ✓ Exposure to irradiance and temperature-controlled testing chambers.
- ✓ Discussion on PV degradation analysis, spectral response, and efficiency benchmarking.

Learning Outcome:

Participants learned how PV modules are tested and validated before deployment and how data supports reliable inverter operation.





Day 2 NCPRE Solar Cell Fabrication & Characterization Facility

Day 2 included a visit to the National Centre for Photovoltaic Research and Education (NCPRE) labs, which are among the most advanced solar fabrication facilities in India.

Key Highlights:

Tour of state-of-the-art clean rooms and cluster tools used for thin-film and crystalline silicon solar cell processing.

Demonstration of:

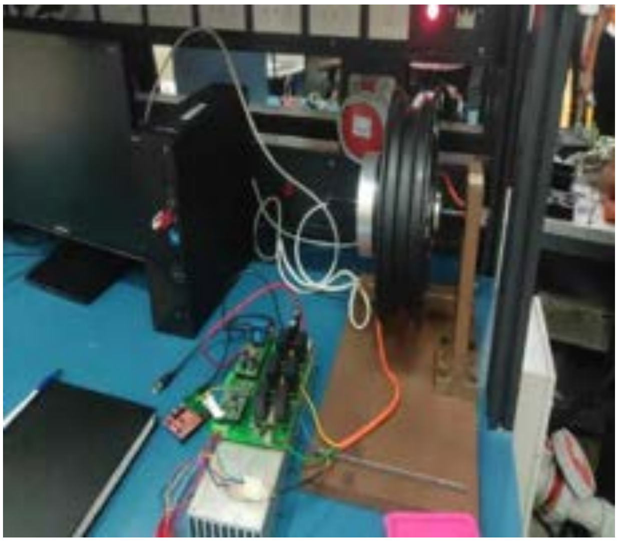
- ✓ Spin coaters used for thin film deposition
- ✓ Evaporators and sputtering systems for material layering
- ✓ Glove boxes with inert atmospheres for sensitive chemical processing
- ✓ Real-time view of solar cell patterning, doping, and annealing stages.
- ✓ Introduction to solar cell efficiency testing, spectral response measurement, and surface texturing tools.

Learning Outcome:

Participants gained insights into how solar cells are fabricated from wafer to device level, and how precision equipment and controlled environments are critical for high-efficiency cell development.

Photographs of Lab Equipments :

1. C1973 EV Power Train Lab





2. NCPRE Solar Cell Fabrication & Characterization

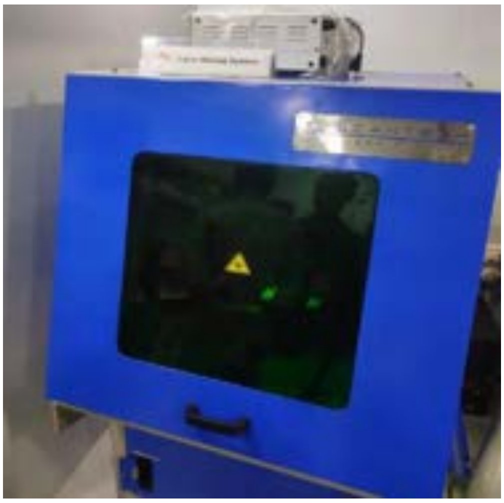


Photo Session

Group Photo At IITB Main Gate

With Our Gurdian Dr. Shinde Sir

With Dr. Diksha Makwani Mam, Senior Executive Officer, NCPRE

Conclusion

The three-day training program on “Advanced Power Electronics for Solar PV Integration”, organized by the National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay, offered an exceptional blend of academic rigor, practical insights, and hands-on experience.

The program emphasized system-level thinking, combining semiconductor device physics, control theory, thermal design, and system safety critical for deploying next-generation solar PV power conversion systems.

Visits to advanced laboratories such as the EV Powertrain Lab, Medium Voltage Power Electronics Lab (MVPEL), and NCPRE Solar Fabrication Labs provided a first-hand look at industrial-grade testing and prototyping infrastructure.

Overall, the training equipped participants with future-ready knowledge and skills to innovate, implement, and lead in the evolving domain of renewable energy systems and solar power electronics.

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